AN IMPROVED METHOD OF ANALYSING DISTORTION IN FOSSILS

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ABSTRACT. Fossils distorted by tectonic strain can be reconstructed to their original shape if the strength and direction of the principal axes of strain are known. The ratio and orientation of the principal strains can be calculated by measuring the distortion in the angle between the median and transverse line in bilaterally symmetrical fossils like brachiopods and trilobites by several methods:

a. They can be determined with exactitude if two such fossils are found on one bedding plane.

b. If a number of single fossil specimens is available, but the relative orientations of their median and transverse lines from specimen to specimen are unknown, the amount of deformation can be calculated by Breddin's method, making use of the most strongly deformed former right angle in the collection.

c. When the principal strain ratios have been calculated, the orientations of the principal axes of strain can be determined in any single specimen.

The different processes are greatly simplified by a special device described in the text.

IN 1962 I described a method for determining the amounts and orientations of the principal strains produced by homogeneous strain in bilaterally symmetrical fossils if two such fossils are found on the same bedding plane. A method based on the same principle was first employed by Lake (1943) who applied it to cases where one of the two fossils had remained right angled. When I wrote my first paper on the subject I was unaware of Lake's work.

The methods described in 1962 give good results, but they are time-consuming. For palaeontologists who have frequently to deal with distorted fossils, as well as for structural geologists who may wish to use distorted fossils to determine the amount of compression of rocks, speedier methods are desirable. Rapid methods for calculating the strains are presented in this paper. When the amount of distortion has been calculated the original form of the fossil may be reconstructed using the techniques employed by Lake (1943), and Sdzuy (1962), and other authors cited by the latter.

Distortion of fossils is rather the rule in geosynclinal strata. In Cambrian strata from different regions of Spain, for instance, deformation of about 60–70% is frequent.

THE PRINCIPLE EMPLOYED

For determining the amount of distortion only the angle between median and transversal direction in bilaterally symmetrical fossils need be measured. This angle may be called β; it is constantly 90° in undistorted specimens. In deformed fossils β may remain 90°, or it may be either increased or decreased, and it can be measured directly in the distorted specimens (text-fig. 1). There are for each fossil two complementary angles β, enclosing together 180°. The tables, etc., in this paper are calculated for the obtuse angle β.

D indicates the amount of deformation as expressed by the ratio of the shortest to the longest axis of the strain ellipse. $D = 50\%$ could mean that the specimen has been compressed to 50% of its original extent parallel to the short axis of the ellipse and remained

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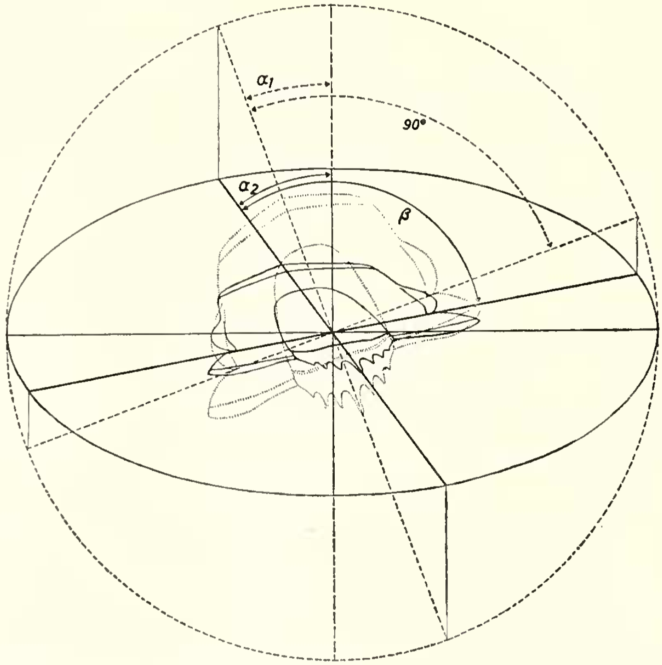
unchanged parallel to the long axis. The direction of the short axis may then be presumed to be identical with the direction of deformation. A ratio of 50% could also have been produced if the specimen is stretched to 200% of its original extent parallel to the long axis and left unchanged parallel to the short axis of the ellipse, and still other processes are possible. The fossils restored by the methods described here will in any case show the original ratio of length/width.



TEXT-FIG. 1. Relationship between undistorted and distorted fossil.

Interrupted lines: Undeformed cranidium of a trilobite drawn into a circle. Its main axes (transverse and median) include a right angle; the main axes include with the direction of later principal strain two acute angles α_1 (only one of these complementary angles is indicated).

Full lines: Effects of deformation ($D = 50\%$). The circle is deformed into an ellipse. The right angles between the main axes of the fossil are changed into angle β (only obtuse angle β indicated). Angle α_1 is changed into angle α_2.

The size of β depends not only on the amount of deformation (D), but also on the size of the angle between the sides of β and the direction of principal elongation (text-fig. 1). If this angle is 0°, that is if one of the sides of the original right angle is parallel to the direction of deformation, β will be a right angle regardless of the amount of deformation. The angle β is made up of two angles, α_1 and $90-\alpha_1$ before deformation, and α_2 and $\beta-\alpha_2$ after deformation. The effects of deformation (D) upon angle α_1 can be expressed as follows:

$$\tan\alpha_2 = \frac{\tan\alpha_1 . 100}{D} \quad \text{and} \quad \tan(90-\alpha_2) = \frac{\tan(90-\alpha_1) . 100}{D}$$

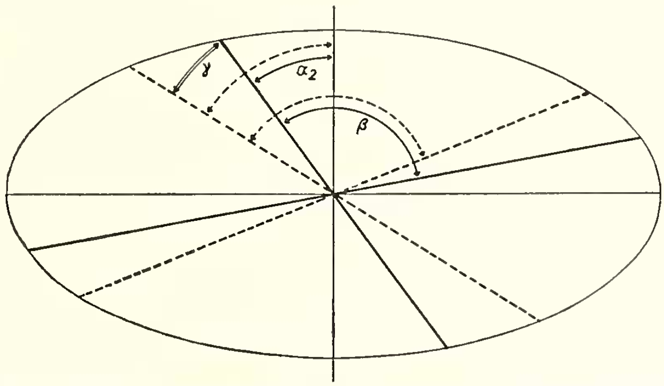
$$\left[\text{or } \tan(90-\alpha_2) = \frac{\cot\alpha_1 . 100}{D}\right].$$

At a given amount of deformation β is greatest if α_1 was 45°. Since tan 45° (and cot 45°) equals 1,

$$\tan \alpha_2 (\text{or } \tan \tfrac{1}{2}\beta) = \frac{100}{D}.$$

Text-fig. 3 shows the combinations β/α_2 at deformations ranging from $D = 100\%$ to $D = 35\%$. A similar figure was published by Breddin (1956, fig. 32).

Since the deformed angle β depends on both D and the size of angle α, different combinations of these two factors may produce the same angle β. Consequently, the amount and direction of the principal strains cannot be deduced from a single angle β.



TEXT-FIG. 2. An ellipse obtained by deformation of a circle, with two different angles β (former right angles deformed by the same strain) drawn (one indicated by a dashed line, the other by a full line). The two angles β are at different angles (α_2) to the direction of principal strain, and consequently their size also differs. The two different angles β and angle γ can be measured in specimens; angle α_2 (necessary for reconstruction of the fossils) can then be calculated.

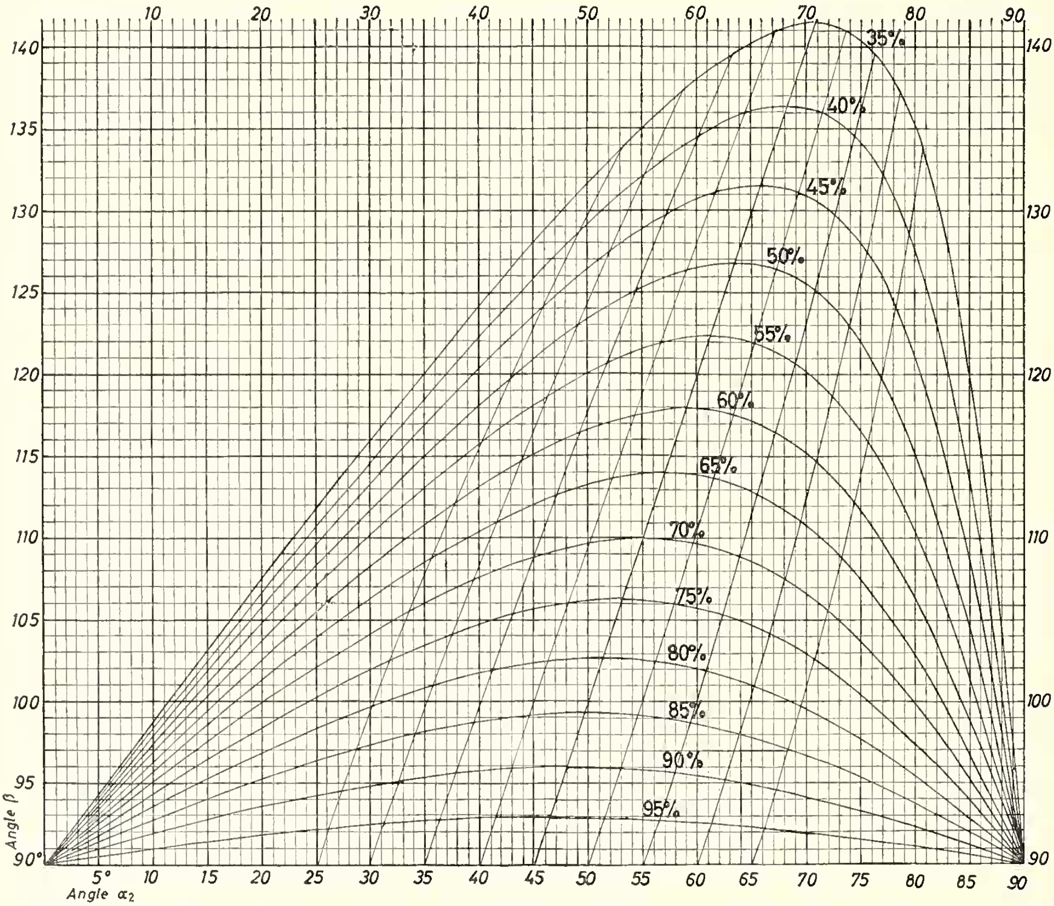
Two fossils on the same bedding plane which have two different angles β are, however, sufficient to determine with exactitude D and α. The relations between two such different angles β, produced by the same process of deformation, may be expressed by angle γ (text-fig. 2), which is equivalent to the difference between the two corresponding angles α_2 and which may be measured in the specimen.

If two different angles β and angle γ are known, D and α can be calculated. The mathematical process is, however, tedious to manipulate and will not be treated here because the indirect methods to find D and α described below and in my 1962 paper are easier and much faster to use. Slight inexactitudes inherent in these methods do not matter because they do not exceed the errors in measuring the different angles in the deformed specimens.

METHODS TO DETERMINE D AND α

1. *If angle γ is not known.* A single angle β does not allow determination of D or α. If, however, a sufficiently large number of specimens showing a single angle β each are at hand and if the mode of their occurrence (same bed and outcrop, homogeneous rock, etc.) indicates that they have been subjected to the same deformation, a method described by Breddin (1956, pp. 264–6) will allow the determination of D and α. It is only necessary to measure the most strongly deformed angle β in the material. If the material consists

of a large number of specimens, one may suppose that in the fossils with the most strongly deformed angle β, angle α_1 was close to 45°, and angle α_2 equals $\frac{1}{2}\beta$. *D* may then be estimated using text-fig. 3 (the apex of the curves representing *D* in the graph indicates the most strongly deformed angle β on the vertical scale of the graph), or it may be



TEXT-FIG. 3. Graph showing the possible combination of angles β and α_2 at deformations ranging from $D = 35\%$ to $D = 100\%$. The graph has been calculated for the obtuse angle β and for the two angles α_2 that make up the obtuse angle β. The lines ascending from the bottom line towards the upper right represent the progressing deformation of angle α_1 into α_2.

calculated: $D = (100/\tan \frac{1}{2}\beta)$. The same equation, but with different symbols and another expression of *D*, was given by Breddin (p. 266). The device described below offers a quick way of measuring β, of discovering the most deformed angle β and computing the value of *D*.

When *D* has been calculated, angle α_2 can be found for any specimen showing a deformed angle β by using the device described below. The graph, text-fig. 3, can also be used for that purpose. The intersection between the curve representing *D* and the horizontal line representing angle β as measured in the specimen will indicate angle α_2

on the horizontal scale. Therefore, if D has been determined for a single specimen (or pair of specimens), all other specimens incorporating a former right angle and subjected to the same deformation can theoretically be restored. In practice, however, a serious drawback to this method is the fact that it is not known from which side of angle β that angle α_2 has to be measured. If angle α_2 is measured from the wrong side of β, β will be a right angle in the restored specimen, but the deformation concerning the ratio length/width of the specimen will be increased instead of eliminated. This effect is nil if the angle α_1 was originally 45° and it increases with decrease in the value of α_1. Where angle α_1 was small (and consequently angle β does not differ much from a right angle), experience with the fossil in question will usually show which position of angle α_2 is the right one.

2. *If angle γ is known.* As already explained, two specimens showing two different angles β on the same bedding plane are sufficient to determine D and α with an accuracy which is only impaired by imperfections of the material. Some of the methods are described elsewhere (Sdzuy 1962); those described here are easier to use.

For a quick determination of D and α, the graph (text-fig. 3) may be used as follows: Measure the two angles β and angle γ, then find in the graph the curve representing D, on which the intersections with the horizontal lines representing the two angles β are separated on the horizontal scale by angle γ. One drawback to this method is that the measuring of the several angles is somewhat tedious; another is that because the curves representing D in the graph have been constructed at intervals of 5%, it is sometimes difficult to locate precisely the two points in the diagram which satisfy the observed angles.

The easiest way to determine the deformation in fossils is by making use of a device which allows direct reading of D and α_2. Such a device is described in the following section.

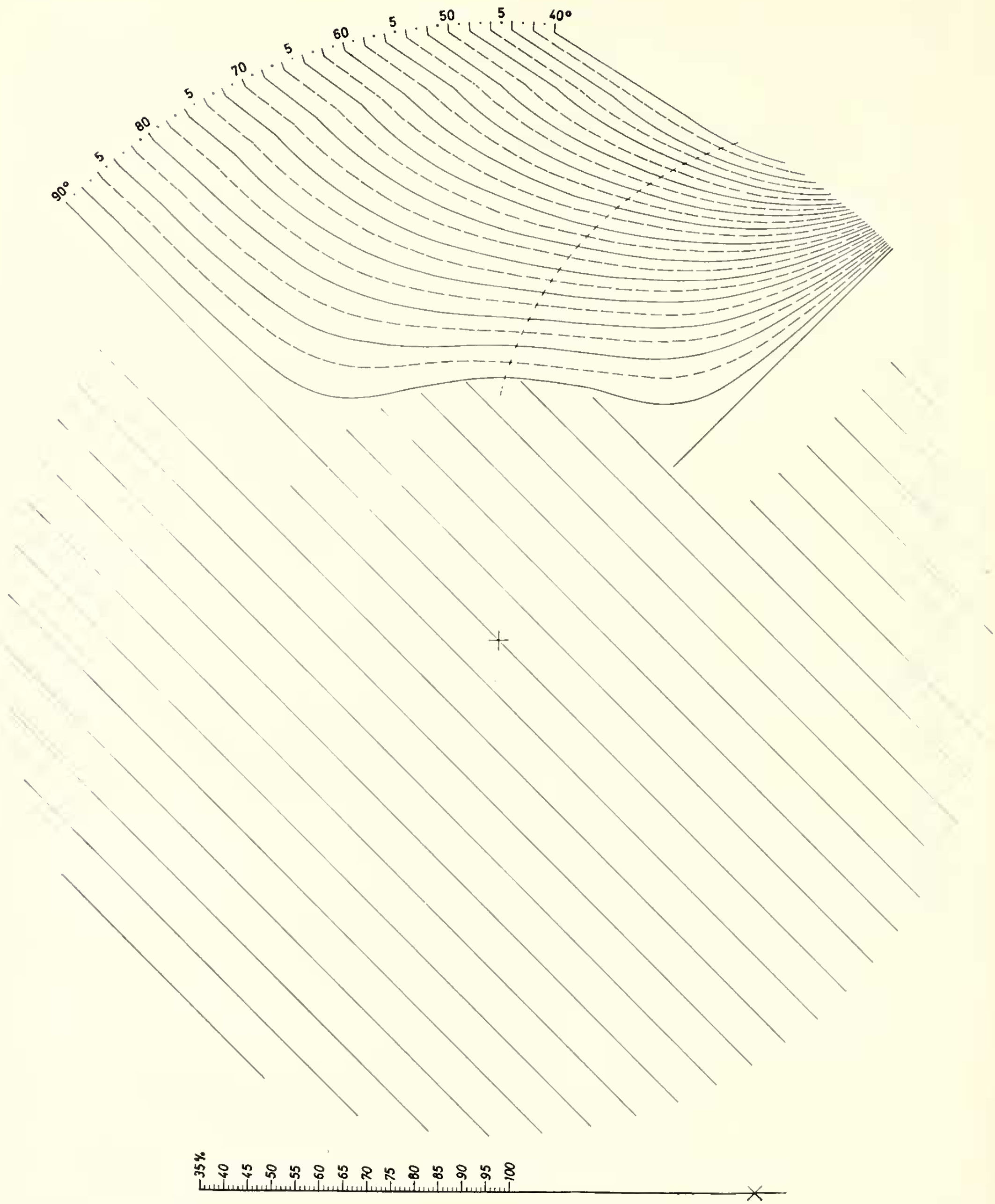
DEVICE FOR DIRECT READING OF D AND α_2

Description. The device is made of four discs of transparent material which can be rotated around their common centre (M in text-figs. 5, 6). Two of the discs (named A for convenience) bear the design shown in text-fig. 4: a set of parallel lines in the central part and a set of curves.

The other two discs (B) bear the following design: one line through the centre and a marker (*m* in text-figs. 5, 6). This marker has to be at a distance from the centre which is just a little greater than the distance of the outer margin of the curve-design in disc A from the centre. The connecting line between this marker and the centre of disc B must be at right angles to the line through the centre. The design of disc B is indicated in text-figs. 5 and 6.

In addition to discs A and B, a ruler is needed (text-figs. 4, 6), on the scale of which the amount of D is indicated. It is convenient to fix this ruler, also moveable, to the common centre of the four discs.

The most important and also the most complicated part of the device is the design in disc A. If one wishes to make a device as described here, one may do so by simply reproducing text-fig. 3 photographically and enlarging it to a convenient size on sheets of clear film. Care must be taken that the ruler (also shown in text-fig. 4) is reproduced at



TEXT-FIG. 4. Disc A and ruler. Both must be reproduced on exactly the same scale. The mode of construction of the curves in disc A is explained in text-fig. 5. The centre M is indicated by a cross in the central part of disc A and on the ruler. On the scale in disc A the number of degrees of the acute angle β will be indicated by the marker of disc B (the corresponding obtuse angle β equals 180 − acute angle β; angle α_2, as needed for the construction of the curves, is obtained by subtracting the acute angle β

exactly the same scale as disc A. The two sheets of film, corresponding to discs A, may then be placed between two plates of glass or some stiff transparent plastic, into which the simple design of disc B has been scratched. The ruler also can be made of transparent plastic. A small screw through the centre of the discs and through the ruler will hold them in place and allow them to rotate against each other.

Each of the curves in disc A represents for a given angle β the possible values of angle α_2 at deformations ranging from $D = 35\%$ to $D = 100\%$. The mode of construction of these curves is explained in text-fig. 5. The intersection of the two curves for two different angles β in their natural position (separated by angle γ) will then show the correct angles α_2 for the two deformed fossils.

Use of the device. 1. To determine D and α_2 from two specimens on one bedding plane, proceed as follows (see also text-fig. 6):

a. Place the device over the bedding plane with two deformed specimens (or, better, over a photograph of the same on which the two angles β have been drawn with ink).
b. Make the lines in the central part of one of the discs A parallel to the *right* side of one of the *acute* angles β (or to the left side of the corresponding obtuse angle β). The line in the central part of one of the discs B must be parallel to the *left* side of the same acute angle β. Do the same with the other two discs for the other angle β, without changing the position of the device.
c. Follow the two curves indicated on the two discs A by the markers of the corresponding discs B to their point of intersection.
d. Place the ruler over this point of intersection, so that the centre M of the ruler coincides with the centre of the discs. The direction of the ruler is then equal to the principal axes of strain, and the point of intersection of the two curves will indicate on the scale of the ruler the exact amount of deformation.

2. If Breddin's method has to be employed, only one pair of discs A and B is needed. Proceed as follows:

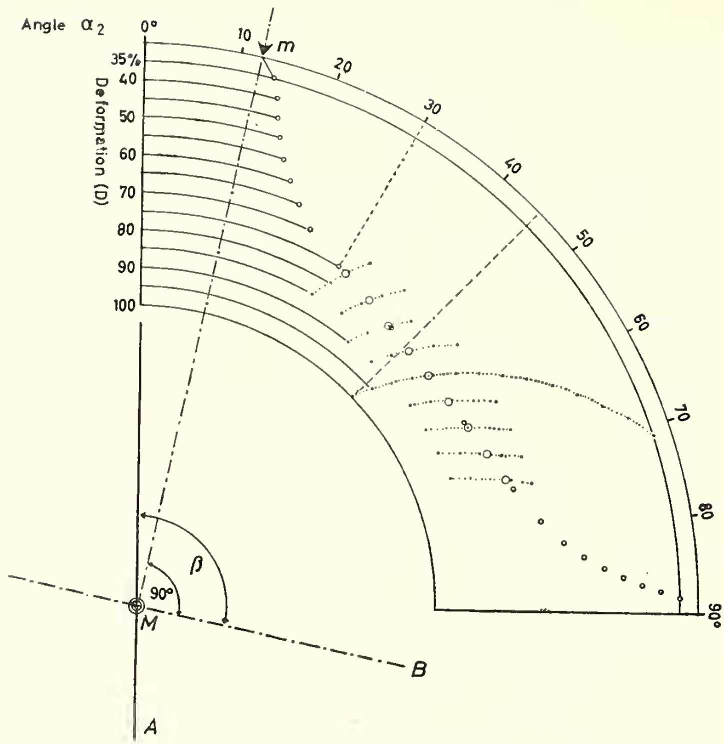
a. To find the most deformed specimen, the device serves as a convenient angle meter; if the lines in the central parts of the discs are parallel to the sides of angle β, the marker of disc B will indicate the number of degrees on disc A.
b. The point of intersection between the curve representing $\alpha_1 = 45°$ on disc A and the curve of the most oblique angle β indicates the approximate value of D on the ruler (see text-fig. 7).

TEXT-FIG. 4 (*continued*)

from 90°). The dashed line cutting across the curves in disc A represents angle $\alpha_1 = 45°$; it helps to find D by Breddin's method.

For the sake of clarity, only those curves corresponding to angles β with a round number of degrees have been drawn. To help avoid confusion of neighbouring curves, every second one has been drawn as a dashed line. The short radial part at the left end of each curve serves to connect the marker of the corresponding disc B with the curve. This radial part may be cut off in one of the two discs A needed and the marker of the corresponding disc B may be placed accordingly nearer to the centre of the disc; this will help to distinguish more easily the two superimposed sets of discs.

The set of parallel lines in the central part of disc A, which has to be parallel to the right side of the acute angle β, helps to measure specimens without rearranging the lines forming the two angles β.



TEXT-FIG. 5. Mode of construction of the curves in disc A, exemplified by the curve corresponding to angle $\beta = 102°$. It is advisable to draw this on a polar stereographic net, as used in structural geology.

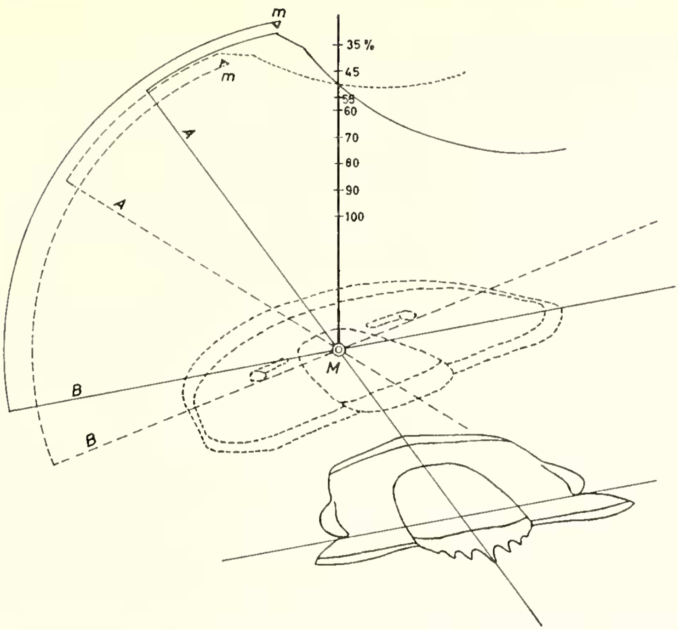
A net is formed by concentric lines, corresponding to degrees of deformation D (indicated only in the left side of the drawing), and by radii, corresponding to angle α_2 (indicated only for $\alpha_2 = 30°$ and 45°). Into this net the horizontal line representing angle $\beta = 102°$ in the graph, text-fig. 3, is transported. (For instance: in text-fig. 3, $\beta = 102°$ intersects the curve representing $D = 75\%$ in the vertical line representing $\alpha_2 = 30°$; the curve constructed in text-fig. 5 has therefore to intersect the concentric line representing $D = 75\%$ on the radius that corresponds to $\alpha_2 = 30°$.) Points found in this manner are indicated by small circles.

Those points are sparse in the middle part of the curve. Additional points may be found here by transferring the lines representing the changes of angle α_1 from the graph, text-fig. 3, into the net (indicated by small points, all of them drawn for the line corresponding to $\alpha_1 = 45°$ only). The points of intersection of those lines with the horizontal line representing angle β can then be transferred from the graph into the net. Points found in this manner are indicated by larger circles.

On the outer circumference, beyond the concentric line corresponding to $D = 35\%$, the intersection with the radius corresponding to angle $\alpha_2 = \beta - 90°$ is marked. (Where $\beta = 102°$ is chosen as example, this is the radius corresponding to $\alpha_2 = 12°$.) This point is connected to the end of the curve which is on the concentric line corresponding to $D = 35\%$. This point will be aligned to the marker of disc B if the lines in the central parts of the two discs include the angle β, to which the curve corresponds.

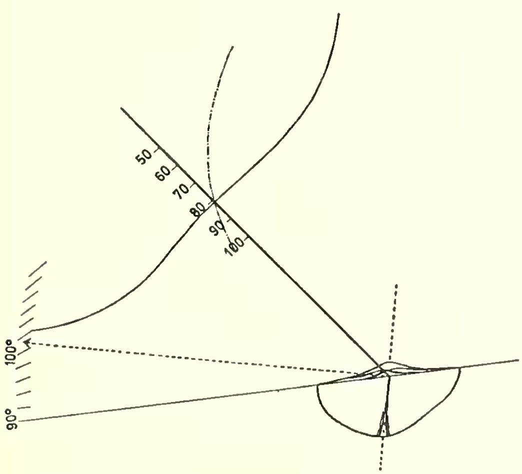
The lines in the central part of disc A have to be parallel to the radius corresponding to $\alpha_2 = 0°$.

The design of disc B is indicated by dotted lines: a line, or a system of parallel lines, in the central part and a 'marker' (m) at right angles to it. (The thin line connecting M and m is not necessary on disc B; it has been drawn to show the position of m.) The lines in the central parts of discs A and B include an angle of 102° (or 78°), and consequently 'm' is aligned with the starting point of the curve corresponding to $\beta = 102°$ of disc A.

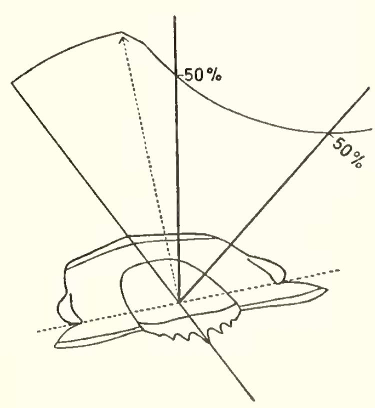


TEXT-FIG. 6. Use of the device to determine D and α_2, exemplified by two distorted cranidia of trilobites. One cranidium, its main axes forming angle β, and the elements of discs A and B corresponding to it, are drawn with dashed lines. The other cranidium and elements of the discs corresponding to it are drawn with full lines (one axis of this cranidium is transferred into M). The ruler is indicated by a heavy line.

The lines in the central parts of discs A and B (indicated by letters in the drawing) are parallel to the axes of the fossils. The markers '*m*' of the two discs B indicate a curve each on the corresponding disc A. The point of intersection of the two curves indicates on the ruler a deformation of 50%; the ruler, placed over the point of intersection, is parallel to the direction of deformation. Distortion of the two fossils in text-fig. 5 would be eliminated after stretching them to twice their extent parallel to the direction of the ruler.



TEXT-FIG. 7



TEXT-FIG. 8

TEXT-FIG. 7. Determination of D with specimen in which angle β is most strongly deformed (indicated by a brachiopod). See text. Angle β of the specimen is 102° (or 78°); D is then about 81%, as can be read on the ruler.

TEXT-FIG. 8. Distorted fossil. D is known (50% in this case). Two different positions of the ruler are possible; one of them is parallel to the direction of principal strain. The marker of disc B is indicated by an arrow in text-figs. 7 and 8.

3. If D is known, α_2 can be found in any single specimen as follows (see also text-fig. 8):

a. Make the lines in the central parts of a single pair of discs A and B parallel to the sides of angle β.

b. The point on the ruler corresponding to D is then placed on the curve of disc A indicated by the marker. Of the two different positions of the ruler, one is parallel to the direction of deformation.

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